

Dangerous ice phenomena on the lowland rivers of European Russia

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Abstract In the Russian climate, the security of populations and economic security are often limited by dangerous ice phenomena. Not only ice-jam floods, but also some processes lead to the violation of operating conditions of various facilities (water intakes, roads, bridges) and damage hydraulic structures and shipping. Currently, rivers' ice regime characteristics change under the influence of both natural (primarily climatic) and anthropogenic factors. Changes have been analyzed in detail on the basis of observations of 300 hydrological stations in the period from 1936 to 2013. Changes of ice phenomena hazards have been estimated. Hazard assessment of flooding caused by ice jams has been carried out for the Northern Dvina River reach from the Velikiy Ustyug City to Kotlas, the most problematic ice jam flooding area in European Russia. The modeling was performed on the basis of *STREAM_2D* software complex for current conditions and taking into account the possible construction of various protective structures. Methods for the prevention of negative impact of water at the site are examined.

Keywords River ice · Dangerous hydrometeorological phenomena · Ice-related floods · Hydrodynamic modelling

1 Introduction

In northern countries, including Russia and Canada, population and economy security is often limited by dangerous ice phenomena. Many economic activities are related to the timing and duration of the ice phenomena. Ice phenomena and processes lead to the violation of operating conditions of various facilities (water intakes, roads, bridges), damage hydraulic

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structures and impede winter navigation on the rivers. In many cases, ice phenomena are responsible for dangerous hydrological processes, including floods; often it is not just ice phenomena, but an adverse combination of dangerous effects of water and ice regime and riverbed evolution. On the other hand, river ice may be useful, for example, to arrange ice crossings (Ashton 1986; Hicks and Beltaos 2008; Buzin 2008).

A list of dangerous hydrometeorological phenomena and processes, including those caused by the ice regime of rivers, is given in Roshydromet's regulatory document (Rushydromet 2008). Information on ice troubles on the rivers is also presented in (Gosstroy of the USSR 1995; USACE 2006). The generalization of this information has resulted in the classification of dangerous ice phenomena and processes in Russia (Table 1).

Hanging ice dams and ice jams take a special place among dangerous ice phenomena and processes. Congestion of ice or sludge in channels results in a sharp rise in water level, often flooding. On large Russian rivers flowing from south to north (the Northern Dvina, the Pechora, the Ob, the Yenisei, the Lena and others), ice jam stages during spring ice run are often higher than the maximum water levels during flooding. Ice jam floods are particularly dangerous because they occur in cold seasons and are accompanied by an ejection of ice on the shore that breaks structures located within the flood zone. The damage caused by ice jams typically far exceeds the damage caused by floods in the ice-free period. In addition to flooding and damaged hydraulic structures, prolonged ice jam delays the cleaning of the river of ice, reducing the navigation period. Rises of water level below hydroelectric dams caused by ice and sludge jams result in a reduction of power production (Buzin 2004; Beltaos 1995).

Ice jams are an important feature of the ice regime of rivers that flow from south to north. If the process of spring breakup propagates from the upper to the lower reaches, ice jams in the breakup period occurs annually, but do not always lead to extensive damage. Delaying the ice and thus providing an opportunity to scatter ice masses downstream, they to some extent normalize an ice run. After a severe winter, ice jams are formed in the upper reaches of the basin due to an abundance of ice material and then, under favorable weather conditions, delay breakup until the rivers are free from ice for a sufficient distance. When the amount of ice is small, ice floe stoppage occurs significantly lower down the stream. The distribution of ice jams along the river also depends on water discharge during breakup. Powerful flood waves push the ice over a greater distance, and ice jams are formed further downstream than in years with low water discharge (Agafonova and Frolova 2007; Agafonova and Frolova 2010).

High water levels in the ice phenomena period can result in damage to hydraulic structures (dam slopes, levees, bridge pillars, ice chutes) and fleet not only during ice and sludge ice jams formation, but also during breakup, thermal expansion of ice and ice piling (Gosstroy of the USSR 1995).

Table 1 Dangerous ice phenomena in Russian rivers

Engineering problem	Ice phenomena and processes
Increased water levels and flooding	Ice jams, hanging ice dams
<i>Violation of operating conditions of various facilities</i>	
Water intakes	Through freezing, underwater ice
Ice crossings	Low strength and thickness of ice, unstable freeze-up
Roads and bridges	Icing (aufeis)
Water transport	Early dates of ice appearance, late breakup and ice clearing at low water level
Damage to hydraulic structures and fleet	Ice run at high water level, ice pile-up

Other dangerous ice phenomena and processes are related to the violation of operating conditions of various objects. For example, the formation of frazil ice near the water intakes and other hydraulic structures interferes with the work of these systems, picks up stones and electric cables from the bottom of the river and pulls piles hammered into the ground (Kozlov 2015). The freezing of rivers to the bottom and the reduced flow in winter cause difficulties in water supply. Mainly, small rivers (with a catchment area of 100 km²) totally freeze in the European part of Russia (EPR), but the in Asian part of Russia (APR), especially in the northeast, rivers with a catchment area of 6000 km² freeze completely every year. Freezing of rivers with a catchment area of 20,000 km² is possible (Arzhakova 2001). Icing, formed on almost all the rivers in the zone of permafrost, often threaten the safety of transport, clogging holes in artificial structures and causing flooding of railways and roads and the surrounding areas (Alekseev 1987). Ice cover consisting of several layers separated with water-free hollows can be dangerous because vehicles can fall into such hollows.

The early appearance of ice (with a frequency occurrence of no more than once in 10 years) can cause difficulties for inland navigation. The early appearance of ice, especially at low water levels in the river, complicates navigation. In some cases, this may lead to a forced wintering of vessels in unsuitable places (Frolova et al. 2007).

Various activities and technical solutions allow for dealing with ice problems successfully. One of the factors that determine the damage is the frequency of the occurrence of hazardous events. The values within the range of natural fluctuations are expected and considered in the design of systems, but, in modern conditions, repeatability as well as other characteristics of some ice phenomena are often changing. These changes occur under the influence of conditionally natural (primarily climatic) and anthropogenic factors.

2 Changes of ice regime of the rivers

According to annual reports on climate change, the average annual temperature in European Russia rises at a rate of 0.4–0.5 °C every 10 years (Rushydromet 2015). The period with subzero air temperature shortens, average temperatures in this period rise, and the number and duration of thaws increases.

Climate changes observed are followed by changes in the water regime of rivers. The increase in air temperature in the cold period increases the probability of rain instead of snowfall in winter and autumn. Snow–rain floods are observed instead of snow accumulation. Loss of snow accumulation in winter results in a reduction of flood discharge and flood levels. For example, on the River Volga basin, the dates of the beginning of spring floods have shifted 10–15 days earlier. The maximum water discharge in the Oka River and its tributaries has decreased by 20–40 %, and in the rivers of the Lower Volga basin by 40–70 %. The flooding phase in the Don basin has become hardly noticeable (Frolova et al. 2011, 2014, 2015). Low water flow during flood periods leads to the depletion of moisture reserves in the basin by the late summer or early autumn. Of course, it should be noted that the intensity of these changes decreases toward the northeast of European Russia.

To date, there have been many studies of the trends of the rivers' ice regime changes. The results of these studies are summarized in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Barros 2014), SWIPA (Snow, Water, Ice, and Permafrost in the Arctic) et al. (Prowse 2007, 2011; Vuglinsky 2002).

In this paper, we have summarized information on the ice regime of the rivers of European Russia according to observations at 300 hydrological stations in the period from 1936 to 2013. Information on the terms of ice phenomena (appearance of ice, freeze-up,

breakup, beginning of the spring ice run and ice clearance), on their duration (ice phenomena period, ice cover, autumn sludge run and spring ice run), typical water levels during spring ice run and ice jams formation and the frequency of ice jams has been used to characterize ice regimes.

The majority of European Russia ice phenomena are observed every year at a duration of 4 months or more. On the large northern rivers (Onega, Northern Dvina, Mezen and Pechora), ice phenomena are observed on an average from October to May in the Volga basin, November to April, in the Don basin and December to March. The average duration of freeze-up is: in the north of European Russia 150–200 days, in the Volga basin 100–150 days and in the Don basin 100–120 days (Fig. 1).

Inter-annual changes in ice regime characteristics are primarily a function of meteorological parameters and characteristics of the water regime of the river. A variety of natural conditions and climate change features within European Russia allows the identification of the main stages of ice regime change in the current climatic conditions. Changes of ice regime become more significant when moving from the north-east part of European Russia to the south-west, but they are not always expressed in the shift of the timing of ice phenomena or in the average duration of the period of ice. The assessment of trends using Spearman's rank correlation coefficient showed no significant changes for almost all the rivers in the north of European Russia.

Currently, changes in the average timing of the appearance of ice and the freeze-up setting on the northern rivers of European Russia do not exceed 5 days (2 days for the rivers of Pechora basin) compared with the period of 1961–1990. Such small changes are associated not only with a slight increase in air temperature in the autumn prior to the freezing period, but also with the features of the water regime of rivers. Mildness in the temperature regime in the north of European Russia is associated with low water discharge in the early autumn, which often leads to the appearance of ice and freeze-up in dates close to normal or even before normal. Unstable variations of air temperature in autumn lead to a return to above-zero temperatures in November, resulting in floods caused by snowmelt and rains. High water levels in this period contribute to a later freeze-up, increased duration of the autumn ice and sludge run, as well as ice and sludge jam formation. Later freeze-up shortens the operating period of ice crossings, which play an important role in the north of Russia (Fig. 2a).

Changes in the maximum thickness of ice in the north of European Russia do not exceed 10 cm compared with the period of 1961–1990 (Fig. 2b). Prolonged thaw periods (for example, in 2006–2007 and in 2015–2016) lead to winter breakups, which are often accompanied, due to high water discharge, by catastrophic ice jams. In addition to this, the volume of sludge ice in the channel increases. Sludge ice jams formed in this period can develop in future spring ice jams. On the other hand, prolonged thaws result in the reduction of ice thickness and snow accumulation. High levels in the period of ice cover and high sludge ice content in channels create favorable conditions for the formation of catastrophic ice jams during breakup. A negative aspect of ice regime change is the reduction of the operating period of ice crossings due to winter breakups and low thickness and strength of ice.

The dates of breakups on the rivers in the north of European Russia have shifted earlier by no more than 5 days, compared with the period of 1961–1991. The climate becoming milder causes simultaneous breakups in quite extensive sections of the rivers. This enhances the ice jam danger. Low water during spring breakup contributes to stable multi-day ice jams. Long periods of clearing shorten navigation time in the most problematic fairway sections.

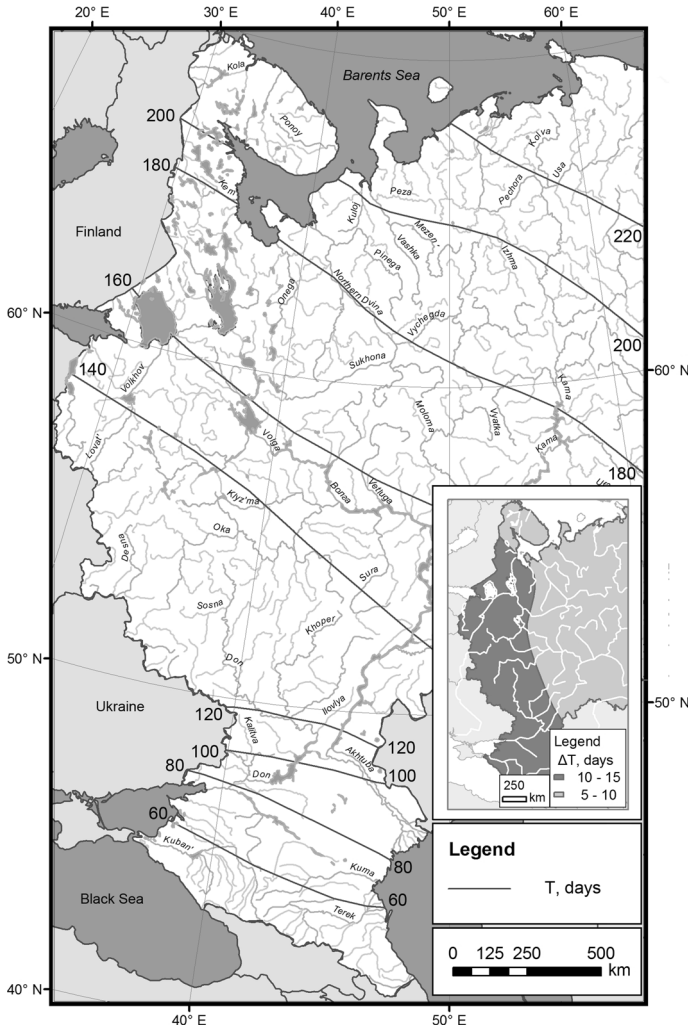


Fig. 1 Duration of ice phenomena period (T, days) and change in one (dT, days) on rivers of European Russia

The dates of the appearance of ice and their changes in the Volga basin are distributed in the territory as follows. On the north of the Kama River basin, ice first appears in late October. Low water discharge in this period and a slight increase in temperature, still below zero, cancel each other out. As a result, the shift in the timing of ice appearance was almost imperceptible and became appreciable only after 2000, when a series of relatively cold years in the 1990s gave way to a relatively warm decade in the 2000s. Due to unstable weather in autumn, the ice cover formed in normal periods tends to break up. It is important to note that the shift in the freeze-up timing occurs primarily due to more frequent cases of extremely late freeze-up. As a result, the duration of the period of freezing increases. On large rivers, for example on the Vyatka, the duration of autumn ice run also increases. In the Upper Volga basin, later transition of air temperature to below-

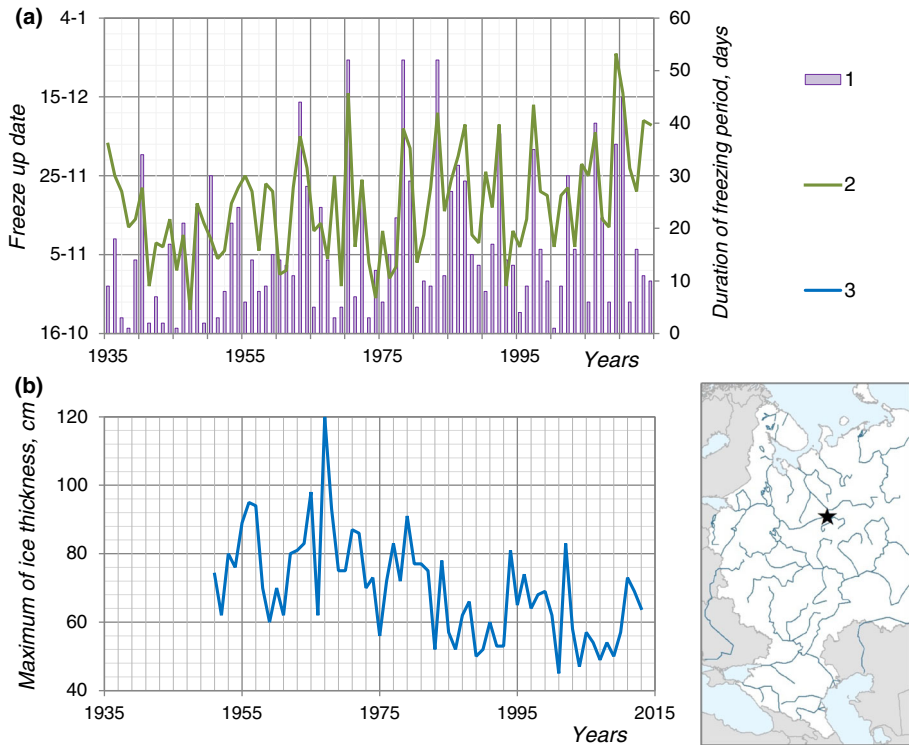


Fig. 2 Changes in the duration of the freezing period (a, 1), freeze-up date (a, 2) and maximum of ice thickness (b, 3) on the Northern Dvina at Velikiy Ustyug

zero values and water discharge increase in the autumn lead to the delay of ice appearance by 10–15 days. For the tributaries of the Middle and Lower Volga, the values of autumn runoff vary slightly; the main factor affecting the timing of ice appearance is air temperature. Time shift on the Middle and Lower Volga is 5–10 days.

In the Upper Volga basin, extremely warm winters have been increasingly observed. In such years, the duration of freeze-up has been sharply reduced and may differ from the average by two to three times (Fig. 3a). The upper limit of the changes of duration varies slightly. The reduction of the maximum thickness of ice is more pronounced (30–50 %) in the south-west of the Volga River basin, where the air temperature in winter more often rises above the melting point when thaws and changes in accumulated below-zero temperatures are more appreciable. In the east of the study territory where the temperature rises but remains below zero all winter, the reduction of the maximum thickness of ice is no more than 20 %.

The breakup of ice in the Volga basin begins usually in early April in the headwaters of the Volga and Oka. Changes in the average dates of breakup are up to 5 days in the southwest of the territory and are almost negligible in the Kama basin. The spring processes tend to begin extremely early. This extremely early spring (late February instead of the beginning of April) is rarely accompanied by a steady transition of air temperature to above-zero values. As a result, cold weather returns during spring breakup, or after clearance, leading to repeated ice runs, which in the composition of the material is more

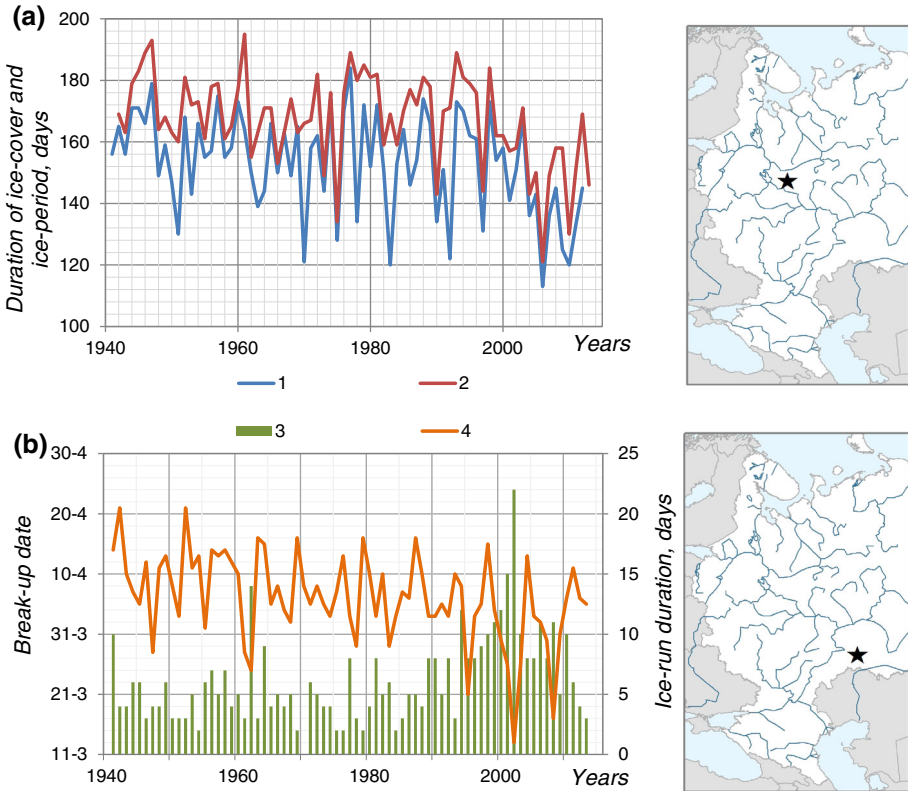


Fig. 3 Changes in the duration of ice cover (a, 1), duration of ice-period (a, 2) on the Kostroma River at Buj and ice run duration (b, 3), breakup date (b, 4) on the Samara River at Elshanka

similar to autumn run than that observed at the spring breakup. In this case, the total ice run duration increases sharply and can reach 40 days, instead of the average values of 5 days (Fig. 3b).

The ice regime of the Don basin rivers is characterized by the period from late November to early April, a freeze-up of short duration or its absence on some rivers (Fig. 4). Climate changes and human impact have led to significant changes in the characteristics of the ice regime. The shift of the average dates of the autumn ice phenomena is about 10 days later, and in spring about 10 days earlier. Prolonged thaws in winter are often accompanied by the clearing of ice from the river, thus splitting the ice phenomena period into two distinct parts.

An important trend in the spring breakup on the Volga and Don basins is a low water discharge during the spring flood and breakup passage; in recent years, it has been observed with increasing frequency. Significant changes in weather conditions in the period leading to the breakup and during the clearing have led to changes in the conditions of breakup throughout the territory and to a reduction of repeatability of spring ice runs in the Don basin. Some time ago, breakups used to occur with the beginning of spring floods, partly under the influence of the growth of water discharge and flow velocity, but in recent years ice has tended to thaw in situ. Reduced water discharge in spring affects the changes

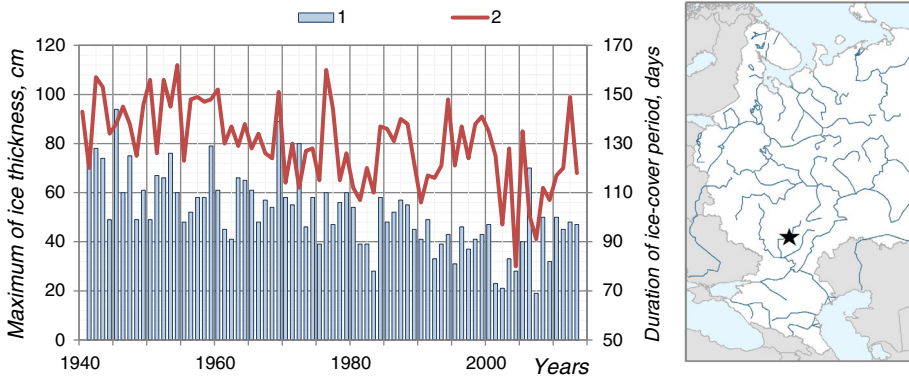


Fig. 4 Changes in the maximum of ice thickness (1) and duration of ice cover period (2) on the Khooper River at Balashov

in water level during breakup; rises in the water level caused by ice jams have been reduced, the water has rarely come to floodplain this period (Fig. 5).

In the current climatic conditions, stable ice cover formation on the rivers in the southern part of European Russia occurs only in some years. Long periods with unstable freeze-up contribute to the formation of tough ice jams including ice blocks, sludge ice and snags. Showers occurring in such periods lead to floods. One of the last such floods was observed in 2002 on the Kuban River (Banshnikova 2013). Thus, in the long run, climate warming leads to a significant reduction in the ice phenomena period and ice regime hazard reduction. But at the moment, changes in usual conditions are creating additional difficulties for the population and the economy.

It should be noted that anthropogenic factors also affect the ice hazard changes. Among these factors is the expansion of human activities: new economic activities for a given area, changes in how land is used, and the expansion of developed areas. Although new dangerous ice phenomena do not occur here, the potential ice hazard is real.

Another anthropogenic factor is hydraulic engineering which actively influences the ice regime and leads to the emergence of hazards that previously were not observed: construction of hydroelectric dams, bridges, the discharge of warm industrial waters, anti-ice jam activities (ice-cutting, ice blasting and icebreaking), various activities causing channel deformation, etc.

3 Assessment of risk of flooding during the formation of ice jams

Ice jams on the rivers in European Russia cause the greatest damage in the period of ice phenomena. Features of the analysis of dangerous hydrological phenomena, and therefore natural risk assessment, depend on the area covered by the studies (Frolova et al. 2015). The size of this area determines the source of information, methods of analysis, selection of appropriate indicators and display features of the phenomenon on the map. In assessing the risk of floodplain flooding due to ice jams, it is possible to utilize data on the height of the floodplain above mean low water level, recurrence of its flooding due to ice jams and the depth of flooding at the maximum ice jam water level of 1 % probability (Kozlov 2015). A parameter that takes into account the excess of ice jam water level above the river banks

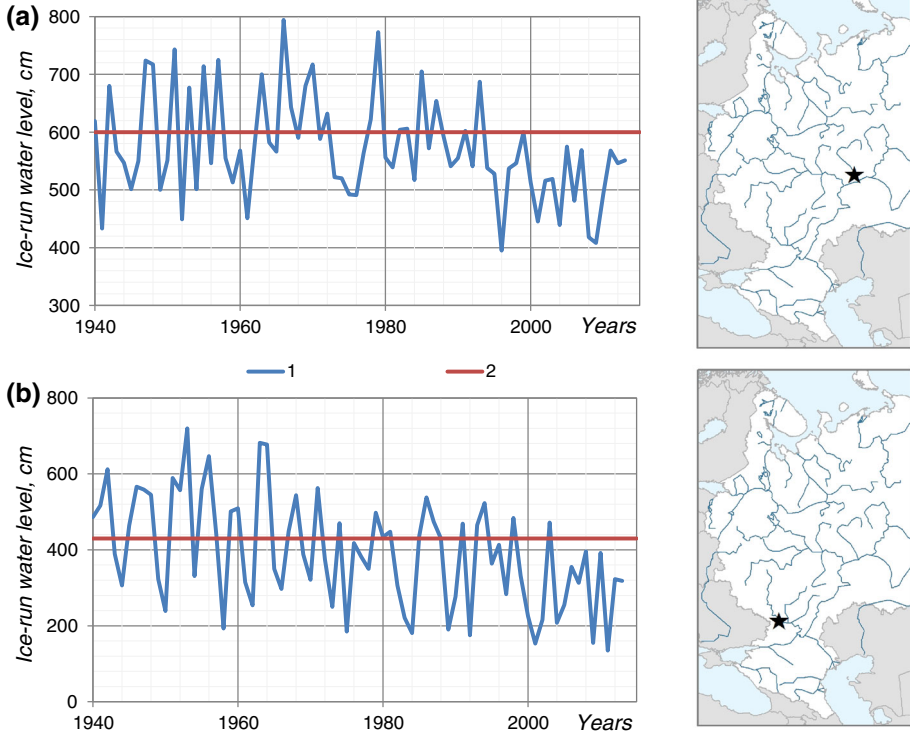


Fig. 5 Changes in the maximum ice run level (1) on the Vyatka River at Vyatskie Polyany (a) and on the Don River at Kazanskaya (b). 2—level of floodplain. Post-zero: the Vyatka River at Vyatskie Polyany—54.83 m BS, the Don River at Kazanskaya—57.98 m BS

and the probability of occurrence of this event may be taken as an index of the potential risk of ice jam flooding:

$$D = (H_{1\%} - H_{\pi}) \cdot (1 - p), \tag{1}$$

where $H_{1\%}$ —estimated level of 1 % probability (cm), H_{π} —the height of the floodplain above mean low water level (cm) and p —recurrence of floodplain flooding (decimal fraction).

As an example, Fig. 6 shows the distribution of the potential risk of ice jam flooding in the basin of Northern Dvina. The ice regime of the Northern Dvina basin is well studied, and significant efforts and material resources are utilized every year to prevent ice jam formation. Additionally, monitoring of spring breakup is carried out by the network of both regular and temporary hydrological stations, and since 2009 the data of satellite images have also been used. However, ice problems of the area have not been fully resolved: damage to shipping companies due to the shortening of the navigation period because of prolonged ice jams, breakage of the pillar of the Kotlas road bridge during the winter breakup in 2006, ice jam flooding in Velikiy Ustyug in 2013, etc. The reach of the Northern Dvina River from Velikiy Ustyug to Kotlas is characterized by one of the highest indexes. A detailed assessment of ice jams danger for this plot was performed.

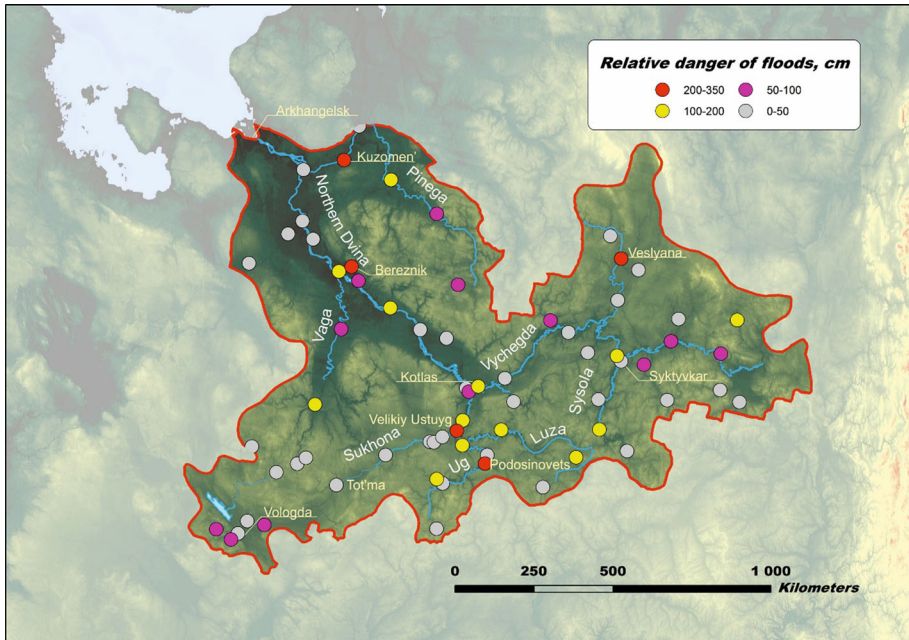


Fig. 6 Map of relative risk of floods in the Northern Dvina River basin

The reach of the Northern Dvina under study, about 90 km in length, is located in the north of European Russia, between the confluence of the Sukhona and Yug rivers (Velikiy Ustyug) and the inflow of the Vychegda River (Kotlas). Five water stage gauges record water levels in this reach, and two of them (upstream) record water discharge. The rivers are mostly snowfed; they show high spring floods and low winter levels. The study section stretches from south to north almost in a meridional direction, so there are powerful ice jams form during breakups on the Sukhona, Yug and Northern Dvina practically every year. The control of accompanying inundations has been an ongoing issue there for more than a century.

The assessment of the possible flood risk requires field studies and a thorough analysis of historical, geographical, hydrometeorological, social and economic information. Additional requirements for this assessment included the development of methods for calculation and prediction of hazardous ice phenomena in view of possible climate change; simulation of manifestations of dangerous hydrological processes based on different scenarios; the evaluation of the probable damage caused by the adverse impact of water, including the analysis of the efficiency of measures against ice and sludge ice jams; and eventually, the development of recommendations regarding protective measures.

The major ice jams are often 10–20 km in length, and their lifetime ranges from several hours to 3–5 days. Nine catastrophic floods, which caused enormous economic damage, were recorded within this reach from 1877 to 2013. The probability of a dangerous water rise during high spring floods due to snowmelt inflow and the back water effects of ice jams in the river reach is about 30–35 % (Fig. 7).

Measures to reduce water level rises caused by ice jams on the Northern Dvina have been carried out since the 1950s. Work for ice weakening (ice blackening and cutting, as well as preventive explosions on the most ice jam-prone zones) are performed before

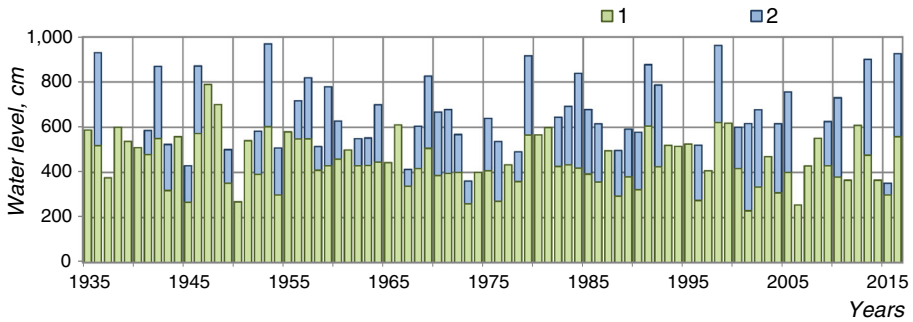


Fig. 7 Changes in the flow component (1) and maximum ice jam water level (2) on the Sukhona River at Velikiy Ustyug

breakups. Ice jams were directly destroyed by explosions (including bombing) or weakened by preventive destruction of ice fields by ice breakers. However, the analysis of long-term fluctuations of the maximum levels induced by ice jams within the study reach over recent decades does not show a significant positive effect of expensive ice jam-control measures on the river rifts located downstream (Buzin et al. 2014). Ice jams form on these rifts almost every year, and only in the case of favorable climatic conditions (a relatively thin and weak ice cover, a low flood wave and slow snowmelt, and the passage of ice runs on the Sukhona and Yug with a time lag) does the spring flood on the Northern Dvina pass without significant damage.

Assessment of the flooded area can be conducted by means of different hydrodynamic models (Pietroniro et al. 2001; Beltaos 2003). STREAM_2D software complex (Belikov et al. 2002, 2015) was used for a mathematical modeling of flooding. The basis of the mathematical model in STREAM_2D consists of the non-stationary two-dimensional equations of Saint–Venant, also known as “the shallow water equations” (Cunge 1980). The two-dimensional equations are discretized on a hybrid triangular–quadrilateral mesh adapted to the channel network. As input data model takes into account a real bed bathymetry and flood plain topography, interpolated onto the centers of mesh cells, using original methods of interpolation (Belikov and Semenov 2000). Water discharge and water levels are necessary as boundary conditions for modeling. Using this simulation, one can evaluate water levels, water depths and mean vertical flow velocities at any point in the study area, as well as the distribution of discharge over the channel branches. STREAM_2D and its previous modifications, named RIVER, BOR and FLOOD, are widely used in Russia and have been applied to flooding simulation in numerous key areas: the Volga, the Amur, the Ob, the Lena, etc. (Zaitsev et al. 2004; Alabyan et al. 2016; Petrakov et al., 2012), including the modelling of flooding zones in the case of dam breaks in the main Russian reservoirs.

The part of the Northern Dvina valley from Velikiy Ustyug to Kotlas, including the confluence of the Sukhona and Yug rivers, with a total length of about 90 km, was included in the hydrodynamic model (Fig. 8). The input data for modeling are based on the data of the riverbed relief, flow velocities, water discharge and water surface slopes obtained from the results of field surveys organized by the Lab of Soil Erosion and River Channel Processes of the Geography Faculty of Lomonosov Moscow State University. Topographic maps, large-scale plans, data of long-term monitoring observations and satellite images have also been used.

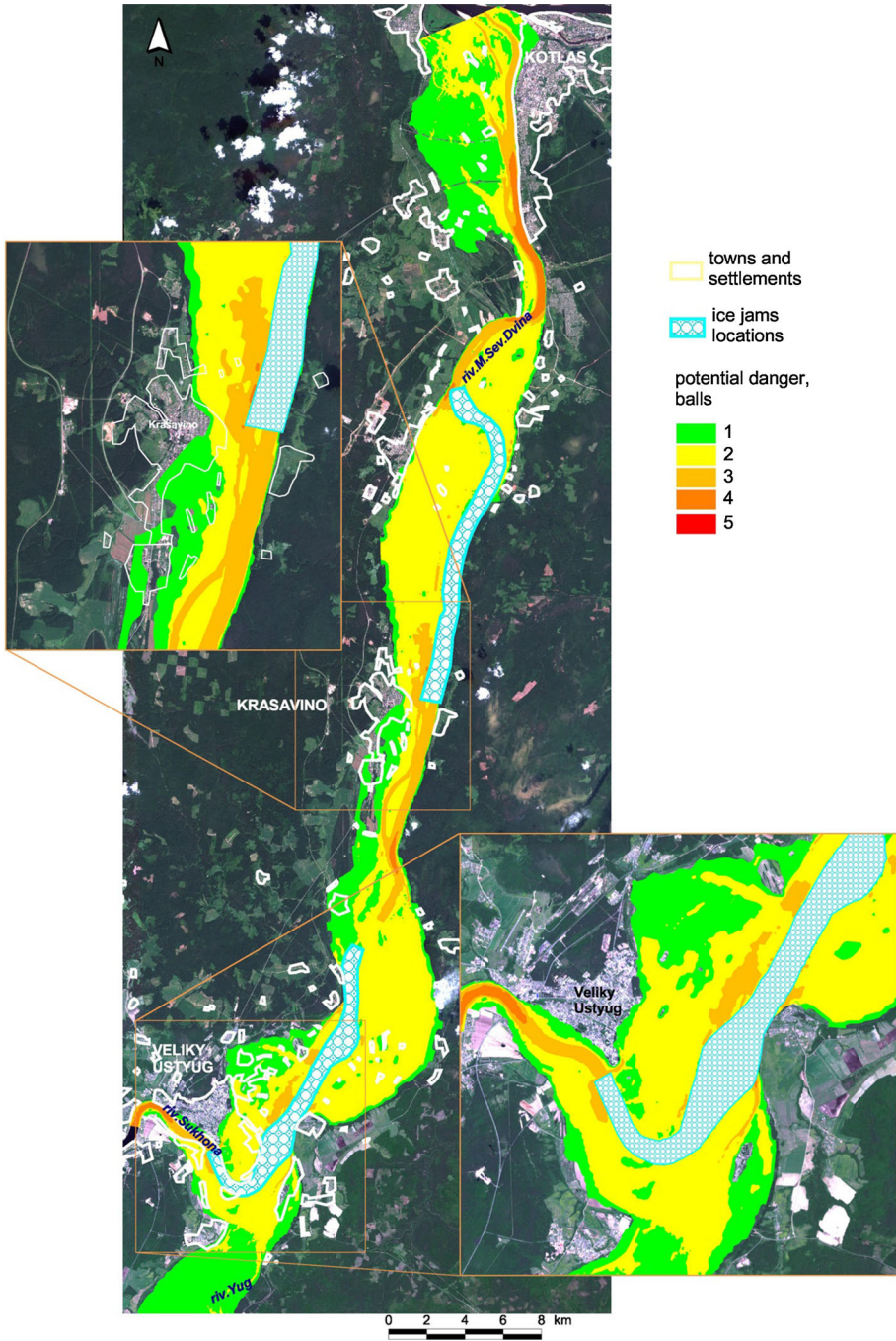


Fig. 8 Map of relative risk of flooding for the section of the Northern Dvina River due to ice jam flood with 1 % rate of recurrence

For model calibration and validation, different scenarios for high flood periods and ice jamming, including the data on the most catastrophic floods in 1998 and 2013, were considered. The water discharge of the Sukhona and Ug rivers at the gauging stations at the upper boundaries of the model, and water levels of the Northern Dvina River at the lower model boundary (Kotlas gauging station) were utilized as the model input. The water levels at the gauging stations located in Veliky Ustug (for the Sukhona River) and in Medvedki (for the Northern Dvina) were used as control points for model calibration and validation. In the case of ice jam formation, the model took into account the location and duration of ice jamming and two additional parameters: the additional ice roughness, and the decrease in the average flow depth due to the river channel filling with ice. Testing of this rather simple approach for the different key study areas (Belikov et al. 2015) has showed that the model can adequately reproduce water levels at the places of ice jam formation.

More than ten hydrological situations including cases of ice jam formation were analyzed. The difference between the simulated and observed water levels at control gauges never exceeded 30 cm. Satellite images have allowed carrying out the additional validation of the model. We used Resource-01 satellite images for the period of high flood at the Northern Dvina River (Veliky Ustyug) in 1998 with a spatial resolution of 30 m and SPOT5 satellite images with a spatial resolution 10 m for the flood of 2012, provided by ScanEx Research and Development Center (Moscow, Russia). Comparison of simulated inundated areas with outlines of flooded zones from satellite images has demonstrated close correspondence (relative errors of 7–8 % in terms of the area for peaks of the analyzed floods). The validation results have showed that the developed hydrodynamic model adequately reflects the real picture of flooding and can be used to assess the possible flooding of the study area in different hydrological situations.

After validating the model, modeling of 1 and 5 % exceedance probability floods was performed, and the flood risk and efficiency of large-scale levees were analyzed. The available observational data of 1896–2013 were used to calculate the maximum water levels for runoff and ice jam-induced floods and maximum water discharge of 1 and 5 % exceedance probability. The simulations for each scenario (for current conditions and for the possible levees construction) have yielded the water levels, water depths, and flow velocities at each cell of the model domain. The modeling has showed that the water levels formed by runoff of 1 % recurrence (which results from a combination of 6500 m³/s discharge for the Sukhona and 5000 m³/s for the Yug) can exceed the low water levels by 6–7 m. In this case, more than 90 % of the river valleys can be inundated, water depths in the flooded part of the City Velikiy Ustyug, situated on a high floodplain, are about 0.5–1 m. In cases of ice jamming, the maximum levels can increase by another 2–3 m. Economic and environmental damage reaches the maximum at water levels at Velikiy Ustyug more than 880 cm above gauge datum. Such levels are repeated once in 5–7 years. The maximum water level of 1 % recurrence (i.e. repeats once in 100 years) is about 1000 cm. Such water levels were modeled as a combination of the maximum runoff observed during ice jams for the entire historical period (discharge of the Sukhona River of 4000 m³/s, discharge of the Ug River of 2000 m³/s) combined with powerful ice jams. In this case, half of the City of Velikiy Ustyug can be inundated with maximum depths of more than 1.5 m. A similar extreme flood took place on 5 May 1998, when the water level at gauge ‘Veliky Ustug’ reached 980 cm.

To assess the potential flood risk on the first step, preliminary hazard maps were developed using the results of hydrodynamic simulations.

Identifying hazard zones is possible using Russian EMERCOM flood hazard criteria, which was developed using statistical data on damage from flooding with a combination of

certain characteristics of the flow (Poljakov et al. 1993; Belikov 2005). In simplified form (Kidyayeva et al. 2013), it allows for zoning the territory into five classes of danger (1 corresponds to minimal, 5—to very high hazard) depending on the specific energy of flow and probability of flooding. Flow intensity could be characterized using specific energy of flow (Belikov 2005), which is calculated with the following formula:

$$P = 0.5\rho H v^2,$$

where P —specific energy of flow (kg/s^2), ρ —liquid density (kg/m^3); H —flow depth (m), v —modulus of flow velocity (m/s).

The potential hazard for flooding induced by ice jam (such flooding occurring in 1 % of cases) has been estimated on the basis of this scale for the Northern Dvina floodplains (Fig. 8) is 2–3 points (from low to medium) that exceeds by 1 point the hazard of runoff-induced flood of 1 % exceedance probability in the same areas.

Developing adequate measures for flood protection for Veliky Ustyug City and the surrounding territory is still a problem. Analyses of different types of levees have shown (Fig. 9) that such constructions, on the one hand, should be rather long (8–12 km) and thus are correspondingly expensive; on the other hand, they will lead to significant flow constriction and concentration on the floodplain. For an extreme runoff and ice jam-induced flood, levee construction would increase water levels throughout the levee length along the Suknona River by more than 1.2 m (Belikov 2015).

To evaluate the economic efficiency of levee construction, the cost of levee construction was compared with potential economic damage from floods. Potential economic damage was estimated on the base of the modeled flow characteristics for scenarios of runoff and ice jam-induced floods of 1 and 5 % exceedance probability. The method of assessing the economic damage caused by floods, developed by EMERCOM, which is used in Russian practice, was adjusted according to the available statistical information and economic and geographical characteristics of the territory (Shpagina et al. 2005; Zemtsov 2016). In the calculations, the economic damage from the flooding of territories was divided into direct

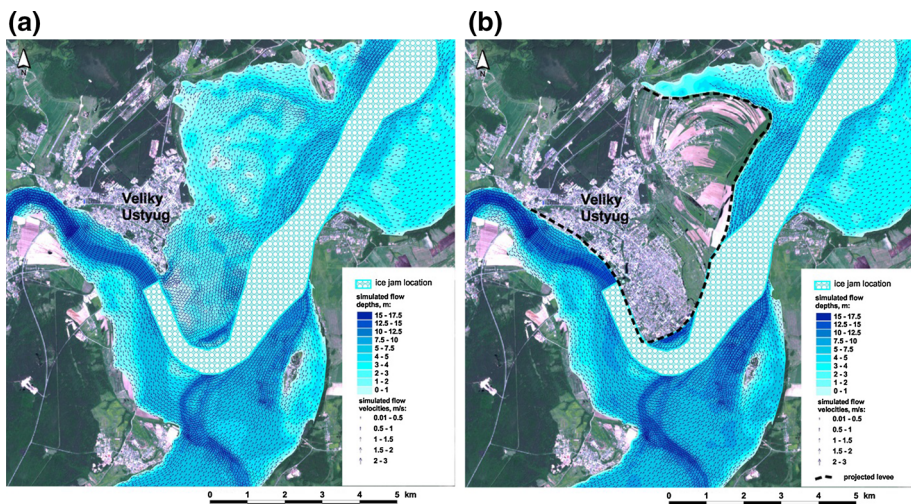


Fig. 9 Simulated water depths and flow velocities at Veliky Ustyug for the ice jam-induced flood of 1 % exceedance probability: (a) for current conditions, (b) in case of levee construction

damage and indirect damage. The direct damage is associated with the direct physical contact of water with economic facilities, the amount of such damage being determined by the cost of restoration of the economy or the current market value of the destroyed (or damaged) economic facilities. The indirect economic losses are due to the shut down of production facilities and plants damaged by floods or inundations. The indirect damage also includes payments for shutdown periods, losses on transport, lost profits, adverse effects of flushed pollutants and damage to sewage treatment plants, manure storage structures, etc.

The initial data for the assessment of damage to productive assets and finished products of companies, housing stock and private property are: data on the population in the flooded zone and elevations of the settlements, as well as the type of residential and industrial buildings which were classified according to the type of settlement.

The calculations allowed estimating the total potential damage in the area of possible flooding. For example, in the case of a flood of 5 % recurrence, it turned out that 70 % of all costs are the costs of housing reconstruction and compensation to the population; 20 % are the costs of the restoration of production facilities; 10 % are the costs of rebuilding the social infrastructure. However, a comparison of the costs of eliminating the consequences of floods and the cost of construction of levee shows that the construction of flood control dams for the cities located on the banks of the Northern Dvina are effective only at a very high flood (1 % recurrence). The efficiency ratio (the ratio of the annual loss to the cost of protective structures) in this case is about 4–5 (Frolova et al. 2015; Kozlov 2015).

The above methods of flood prevention are based on the major hydrotechnical intervention in natural processes of water and stream flow regime. They also involve significant environmental risks. The measures aimed at reducing the ice jam component during the spring flood are not as effective, but are more economical and “soft” for river ecosystems. In particular, the prevention of flooding of settlements is optimal when hydraulic engineering is combined with annual channels dredging.

4 Conclusions

In the Russian climate, the security of populations and economic security are often limited by dangerous ice phenomena. In many cases, ice phenomena are responsible for dangerous hydrological processes including floods. Often, it is not an exclusive action of ice phenomena, but an adverse combination of dangerous manifestations of water and ice regimes, as well as riverbed evolution. Dangerous ice phenomena within Russia include: the formation of underwater and sludge ice, sludge ice jams, the early appearance of ice and freeze-up at low water levels, icing, total freezing, low thickness and strength of ice during freeze-up, thick ice run at high water levels, ice jams, ice pile-ups, late breakup of ice and clearing of ice at low levels. These dangerous phenomena lead to floods, violation of operating conditions of water intakes, ice crossings, railways, highways, water transport, damage to hydraulic structures and shipping and the violation of the existing relations between the population and the economy.

The change in the characteristics of the ice phenomena and processes occurs under conventionally natural (primarily climatic) and anthropogenic factors. A diversity of natural conditions and degree of climatic changes within European Russia has allowed identifying the main stages of the ice regime changes in the current climatic conditions.

The ice regime does not respond immediately to climate change. In general, ice regime changes are more distinct in the west of the territory.

With minor changes, winter breakups and prolonged spring, ice jams tend to occur more often. Next, the dates of freeze-up and breakup shift. The duration of freezing and clearing increases. Unstable weather in the period of clearing leads to recurrent ice formation. Composition of ice material changes, jam formation and sludge ice run, as opposed to ice run, in the spring period are observed more often. Then the dates of ice appearance and clearing of rivers shift, recurrence of spring ice break decreases and the ice tends to thaw in situ. The most significant changes in the ice regime of rivers within European Russia are expressed in the absence of steady freeze-up, and prolonged thaws split the period with ice phenomena into two or more separate parts. In the long term, climate warming leads to a significant reduction in the period with ice phenomena and the decrement of ice regime hazard.

The most problematic section of the Northern Dvina River, in terms of ice jam flooding, is located between Velikiy Ustyug and Kotlas. For this section of the river, the maximum water levels of flow and ice jam genesis, as well as the maximum water discharge of 1 and 5 % recurrence on the boundaries, have been calculated, based on the available observation data of the period from 1896 to 2013. The modeling was performed on the basis of *STREAM_2D* software complex. Two-dimensional Saint–Venant equations were taken as a basis for a mathematical model of flooding. The simulation for current conditions and the possible construction of bank protection dams showed that the water levels that formed by flood runoff of 1 % recurrence may exceed the dry-season levels by 6–7 m. In this case, more than 90 % of the river valleys can be inundated. In the case of the ice jamming, the maximum levels may increase by another 2–3 m. When the level rises to 5–8 m, flooding begins in the territory of Velikiy Ustyug, situated on a high floodplain. The economic and environmental damage reach the maximum at $H > 880$ cm. Such levels are repeated once in 5–7 years. The maximum water level of 1 % recurrence (i.e. repeats once in 100 years) is about 1000 cm.

In the calculations, the economic damage from the flooding of territories was divided into direct damage and indirect damage. The method of assessing the economic damage caused by floods, which is used in Russian practice, was adjusted according to the available statistical information and economic and geographical characteristics of the territory. A comparison of the costs of eliminating the consequences of floods and the construction cost of protection dams shows that the construction of flood control dams for the cities located on the banks of the Northern Dvina are effective only at very high floods (1 % recurrence). The efficiency ratio (the ratio of the annual loss to the cost of protective structures) in this case is about 4–5.

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